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14. ABSTRACT

During the two-year duration of this program, we accomplished or made significant progress in three objectives for specific integrated optical systems. The general technology focus was to develop practical methods for reducing the physical dimensions of optical circuits through manipulation of the device geometry and refractive-index profile and develop several new integrated optical devices on $LiNbO_3$ devices. Our research on $LiNbO_3$ has yielded a new low voltage E/O scanner, techniques for poling thin crystal ion slicing (CIS) $LiNbO_3$ films for integrated photonics applications, and several silicon-on-insulator-based integrated-optic components having new and important functionality.

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New Techniques for Heterogeneous Integration for Optical Sensing Systems

Contract # F49620-02-1-0078

FINAL REPORT

For the period:
11/15/01 – 11/14/03

Submitted by:

The Trustees of Columbia University
Columbia University

Center for Integrated Science & Engineering
and
Microelectronics Sciences Laboratories

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Prepared December 2003

1. Objectives

The objective of this program is to develop new optical devices for integrated optical or integrated optical/microwave RF systems.

2. View of Effort

During the one-year duration of this program, we accomplished or made significant progress in three objectives for specific integrated optical systems, with the general goal being RF/photonics for RF sensing. This work used our capabilities in computer-aided design of optical systems and in new methods of materials fabrication. The general technology focus was to develop practical methods for reducing the physical dimensions of optical circuits through manipulation of the device geometry and refractive-index profile and develop several new integrated optical devices on $LiNbO_3$ devices. Our research on $LiNbO_3$ has yielded a new low voltage E/O scanner and techniques for poling thin crystal ion slicing (CIS) $LiNbO_3$ films for integrated photonics applications. In addition we have realized several silicon-on-insulator-based integrated-optic components, with important new functionality. Several of our efforts have involved outside collaborations, including MIT, IBM, and MIT Lincoln Lab.

3. Accomplishments

a) Poling of Crystal Ion-Sliced (CIS) $LiNbO_3$

Previously, our group has actively pursued methods of incorporating our thin-film CIS technology into novel devices and has successfully introduced CIS into other device technologies; one such technology is periodically poled lithium niobate. We have recently showed that crystal-ion-sliced, periodically poled $LiNbO_3$ can form a low-cost route to on-chip optical wavelength converters. Our initial devices used commercial PPLN, which was then ion-sliced for use for on-chip mounting. We have now developed the capability for doing poling in house as a result of a multiyear collaboration with Gr82 at MIT Lincoln Lab.

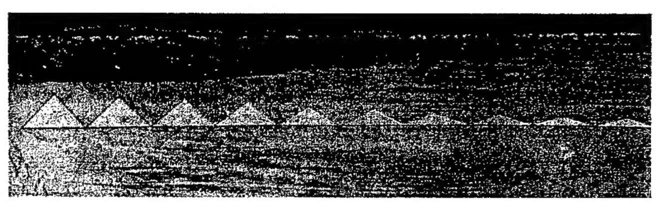

Fig.1. Prism-shaped domains poled in bulk $LiNbO_3$ are revealed by HF etching. These are used in our low voltage E/O scanner.

The goal of our work here has been to develop poling techniques for CIS films. Thus our group entered into a collaboration with Gr82 of MIT's Lincoln Laboratories (headed by Dr. Antonio Sanchez) in order to develop poling techniques for ion-sliced material. Beginning in 2001, we conducted several extended visits to Lincoln Laboratories to perform experiments on our samples and understand which procedures were key. Based on this work, we have recently designed and built our own poling instrument at Columbia. With this technology, we have

learned how to pole complex micropatterns into lithium niobate bulk crystals, which may then be lifted off into thin-film form using our CIS process. This allows us to fabricate devices that utilize the benefits of both technologies simultaneously. In addition to our collaboration with Gr82, we have established a joint effort with Dr. Keith Nelson group at MIT on short-laser pulse acoustic excitation in thin single-crystal films. Our group has recently demonstrated guidance and control of short-pulse laser-initiated phonon-polaritons in both bulk and CIS film ferroelectric crystals. The work has interesting implications for future acoustic filters and signal processing chips. This research was presented at the Fall 2003 MRS meeting and will be published shortly.

b) Low-Voltage Electrooptical Scanner

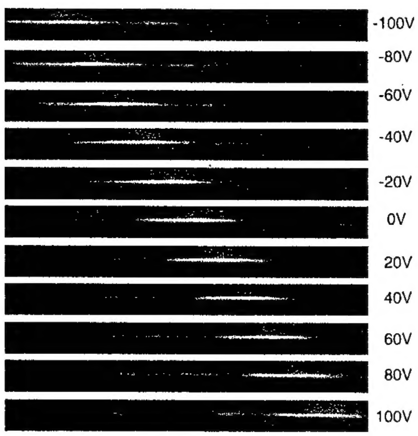

Fig.2. Beam deflection by a CIS film scanner vs. applied voltage

The goal of this project is to demonstrate a low-voltage E/O scanner. The basic approach is to use a CIS $LiNbO_3$ slab waveguide along with vertical metal-electrode prisms. The advantage of the device is its >10 reduction in device voltage due to the thin CIS film; this makes a low-voltage E/O scanner possible.

We have fabricated such a low-voltage E/O scanner by using electric field poling and crystal-ion-slicing of $LiNbO_3$; a micrograph of a poled and sliced device is shown in Fig. 1. The device consists of cascaded E/O prisms defined by polarization inversion of prism-shaped domains in bulk z-cut $LiNbO_3$ wafer. The cascaded prism pattern was photolithographically defined in photoresist using direct laser writing and transferred to a Cr poling electrode (evaporated onto the $LiNbO_3$ sample) after exfoliation following wet etching. The area defined by the Cr electrode was domain inverted by applying a high-voltage pulse between +z and –z sample surfaces. Using our CIS technique, a 10-μm thick layer was sliced off from the surface of the poled bulk sample. Thermal evaporation and conductive epoxy are used to define top and bottom electrodes of the CIS-film device. Experimental data, such as shown in Fig. 2, demonstrate that an angular deflection of around ±1° is obtained for an applied voltage of 100V for the current CIS film scanner. This results agrees well with the theory and *the voltage dependent angular deflection is better than state of the art E/O scanners.* A longer scanner is currently being fabricated and this device will enable a deflection of ~ ±5° for an applied voltage of 80V, as compared to 1000V needed for a bulk device of the same dimensions.

c) Novel Devices of Silicon on Insulator

This project has investigated and fabricated several new optical devices, which are made of silicon on insulator. This materials combination allows high-index-contrast waveguides for ultracompact PICs; it also allows integration with silicon electronic circuitry. To fabricate the devices we have used either e-beam or laser patterning. We have recently fabricated a series of passive devices at Cornell; these devices were then characterized and tested at Columbia

High-Speed Thermooptical Switch

We have designed and fabricated the first Mach-Zehnder interferometer thermo-optic switches using wafer-bonded thin-silicon-on-insulator materials system. The thermally switched devices use single-mode strip waveguides with dimen-

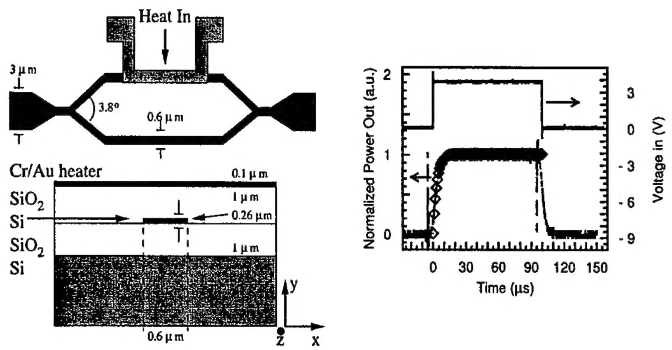

Fig. 1 Schematic of MZI thermooptic switch

sions, $0.26 \times 0.6\ \mu m^2$, operating at a wavelength of $\lambda = 1.55\ \mu m$. Useful device characteristics include a low switching power, 50 mW, and a fast rise time of < 3.5 µs. These results demonstrate the potential of this high-index-contrast materials system for the design of fast and low power thermo-optic switches and as an active element in photonic integrated circuits. Performance of this device was recently expanded on by research in Mike Geis's group at MIT Lincoln Lab.

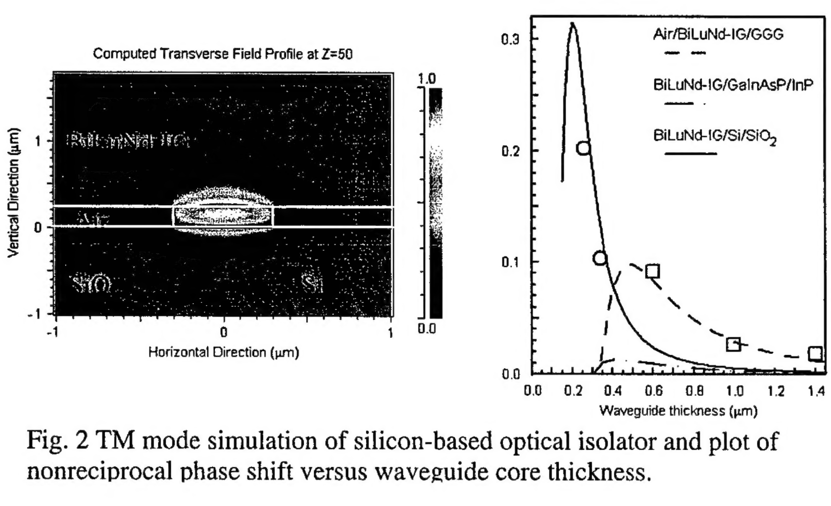

Fig. 2 TM mode simulation of silicon-based optical isolator and plot of nonreciprocal phase shift versus waveguide core thickness.

Silicon-Based Optical Isolator

We have demonstrated the integration of a single-crystal magnetooptical film onto thin silicon-on-insulator (SOI) waveguides using direct-wafer bonding. Simulations and recent experiments show that the high confinement and asymmetric structure of SOI allows an enhancement of ~3X over the nonreciprocal phase shift achieved in previous designs; this value has been confirmed by our measurements. Our structure enables the realization of compact magnetooptic nonreciprocal devices, such as isolators, integrated on a silicon waveguiding platform.

Silicon Raman Optical Amplifier

The goal of this project is to demonstrate a low threshold diode-laser pumped Si-Raman optical amplifier on an SOI chip. We have recently demonstrated spontaneous forward and backward Raman emission at 1550 nm using a 1435 nm pump laser and ultrasmall, low-loss SOI strip waveguides. A group at IBM, led by Dr. Yurii Vlasov, fabricated the SOI waveguides, which have sub-micrometer waveguide core areas (0.1 μm^2), excellent fiber to waveguide coupling via polymer inverse tapers (1 dB for a pair), and very low propagation losses (3.5 dB/cm for TE). We are currently characterizing the waveguides and have determined the Si waveguide material Raman coefficient and waveguide loss. We are currently beginning tests for stimulated Raman emission.

4. Personnel Supported:

a) Research personnel
Jerry Dadap Jr.

b) Graduate students
Juni Fujita – PhD, now at Dupont Photonics
Tomo Izuhara – PhD, now at Dupont Photonics
Richard Espinola
Ryan Roth
George Djukic

5. Publications:

- D.W. Ward, E. Statz, J.D. Beers, N. Stoyanov, T. Feurer, R.A. Roth, R.M. Osgood, Jr., and K.A. Nelson, "Phonon-Polarition Propagation, Guidance, and Control in Bulk and Patterned Thin Film Ferroelectric Crystals." Accepted by Proceedings of the MRS 2003 Fall Meeting, Symposium C - Ferroelectric Thin Films. (2003)

- R. L. Espinola, T. Izuhara, M-C. Tsai, and R.M. Osgood, Jr. "Magnetooptical

Nonreciprocal Phase Shift in Garnet/Silicon-on-Insulator Waveguides." Submitted to Opt. Lett. (2003)

- T. Izuhara, R. Roth, R.M. Osgood, Jr., S. Bakhru, and H. Bakhru, "Low-Voltage Tunable TE/TM Converter on an Ion-Sliced Ithium Niobate Thin Film." Electron. Lett. 39, 1118 (2003)

- T. Izuhara, I.L. Gheorma, and R. M. Osgood, Jr., A.N. Roy, H. Bakhru, Yiheli M. Tesfu, and M.E. Reeves, "Single-crystal Barium Titanate Thin-Films by Ion slicing." Appl. Phys. Lett. 82, 616-618 (200

- R.L. Espinola, M. C. Tsai, J. Yardley, and R.M. Osgood, Jr., "Fast and Low Power Thermo-Optic Switch on Thin Silicon-on-Insulator." Photon. Tech. Lett. 15. 1366-1368 (2003)

- A.M. Radojevic, R.M. Osgood, Jr., A.N. Roy, and H. Bakhru, "Prepatterned Optical Circuits in Thin Ion-Sliced Single-Crystal Films of $LiNbO_3$." Photon. Tech. Lett. 14, 322-324 (2002)

- T. Izuhara, J. Fujita, M. Levy, and R. M. Osgood, Jr., "Integration of Magneto-optical Waveguides onto a III-V Semiconductor Surface." Photon. Tech. Lett. 14, 167-169 (2002)

- R. Ahmad, F. Pizzuto, G.S. Camarda, R.L. Espinola, H. Rao, and R.M. Osgood, Jr., "Ultra-Compact Corner-Mirrors and T-branches in Silicon-on-Insulator." Photon. Tech. Lett. 14, 65-67 (2002)

6. Interactions/Transitions

a. Meetings, Conferences, Seminars

- MRS Fall 2003 Meeting, Boston, Massachusetts, December 1-5, 2003. "Phonon-Polarition Propagation, Guidance, and Control in Bulk and Patterned Thin Film Ferroelectric Crystals." D.W. Ward, E. Statz, J.D. Beers, N. Stoyanov, T. Feurer, R.A. Roth, R.M. Osgood, Jr., and K.A. Nelson.

- . IEEE/LEOS Summer Topicals 2003, Vancouver, British Columbia, Canada, July 14-16, 2003, "High-Index Contrast Bend Structures for Microphotonics." R.M. Osgood, Jr.

- Gordon Research Conference 2003, Mount Holyoke College, South Hardley, Massachusetts, June 22-27, 2003, "Single-Crystal Zinc Oxide Nanowires Grown by Vapor Transport Using Different Metal Catalysts." Z. Zhu, T-L. Chen, Y. Gu, G. Totir, Y. Le, and R.M. Osgood, Jr.

- McMaster Univ. Faculty of Engineering Symposium, McMaster University, Hamilton,

Ontariio Canada, November 11, 2003, "Slicing Metal-Oxide Crystals with Ions." R.M. Osgood, Jr.

- ONR Workshop 2003, Tenaya Lodge, Fish Camp, California, May 4-8, 2003, "Lift-Off and Wafer Bonding of Single-Crystal Metal-Oxide Functional Thin Films." R. M. Osgood, Jr.

- CLEO 23rd Annual Conference 2003, Baltimore, Maryland, June 1-6, 2003, "Thermo Optic Switching Devices in Thin Silicon-on-Insulator." R. Espanola, M-C. Tsai, T. Izuhara, R.M. Osgood, Jr.

- Photonics West 2003, San Jose, California, January 30, 2003, "Design and Fabrication of High-Index-Contrast, Silicon-on-Insulator Photonic Integrated Circuits." R.M. Osgood, Jr.

- OSA Annual Meeting 2002, Orlando, FLA, Sept. 29-Oct. 3, 2002, "High-Index-Contrast Ultrasmall Optical Devices on Silicon-On-Insulator." R. Espinola and R. M. Osgood, Jr.

- CLEO/QELS 2002, Long Beach, CA, May 19-24, 2002. "Channel Waveguides in Thin-Film $BaTiO_3$ for a Low Voltage TE/TM Converter." T. Izuhara, and R. M. Osgood, Jr.

b. Interactions

This project included a significant joint collaboration with the Quantum Electronics Group at MIT Lincoln Laboratory and The IBM T.J. Watson Laboratory.